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Discrimination Options in the Near Term

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DISCRIMINATION OPTIONS IN THE NEAR TERM

by

Gregory H. Canavan and John C. Browne

ABSTRACT

Estimating midcourse threats and deriving optimal numbers of decoys produces an integrated picture of the trades between boost-phase attrition, midcourse defenses, and discrimination. Boost and midcourse interceptors can be effective, but are sensitive to light decoys. If discrimination is not available at the outset of deployment, enough interceptors must be purchased to meet both the RVs and decoys. This initial purchase can be so large that later development cannot offset its impact on discounted costs.

I. INTRODUCTION

This article estimates the sizes of midcourse threats for various boost-phase defensive layers, derives the optimal number of decoys for the offense to use against specified defenses, and discusses the impact of various levels of discrimination on them, which produces an integrated picture of the trades between boost-phase attrition, midcourse defenses, and discrimination.

II. COMBINED DEFENSES

Kinetic-energy interceptors (space-based interceptors [SBIs] and ground-based interceptors [GBIs]) are the most developed concepts in strategic defense. They should be highly effective

against the current missile threat and nominal modifications.[1] Their performance in the boost phase is critically dependent on the spatial and temporal extent of the boost-phase engagement,[2] which is discussed elsewhere.[3] The overall effectiveness of deployments in which they are a layer is also dependent on the effectiveness of downstream layers, which depends on the rate of modernization of penetration aids and the introduction of decoys, which are discussed below.

A. Undecoyed Threats

Absent decoys, a combination of SBIs and GBIs could be effective against current missile threats. In the near term, the boost-phase defender availability is $f \approx 20\%$. Thus, against a simultaneous launch of $M \approx 1{,}000$ missiles, about $K \approx M/f \approx 1{,}000/0.2 \approx 5{,}000$ SBIs should suffice.[4] If their kill probability was near the goal of $p = 90\%$, the defense would then need $I \approx (1-p)mM \approx 1{,}000$ GBIs to handle the $m \approx 10$ reentry vehicles (RVs) on each heavy missile that leaked through the boost-phase layer. For historical kill probabilities, which are closer to 0.6-0.8, 2,000-4,000 GBIs could be needed for even undecoyed threats.

For SBIs costing $C_K \approx \$1M$ and GBIs costing $C_I \approx \$2M$, the interceptors for a purely kinetic-energy defense would thus cost on the order of

$$C \approx C_K M/f + C_I(1-p)mM = [C_K/f + C_I(1-p)m]M, \qquad (1)$$

which for the parameters above gives $C \approx \$1M/SBI \cdot 5K\ SBI + \$2M/GBI \cdot 1K\ GBI \approx \$5B + \$2B \approx \$7B$ for the interceptors, or $C/M \approx \$7M$ per missile engaged. Since heavy missiles have life cycle costs of $C_M \approx \$200M$ apiece, that would give the defense a cost effectiveness ratio of

$$E \approx pC_M M/[C_K/f+C_I(1-p)m]M$$
$$\approx 0.9 \cdot \$200M/\$7M \approx 30. \qquad (2)$$

These interceptor costs could be doubled for sensors and control and easily doubled again for overhead, but even the resulting $\approx$ \$30B per missile intercepted would still be effective by a factor of ≈ 7 relative to current threats. This margin could

gradually be eroded by modernization of the boost-phase threat in space and time, but that is not the concern here. The discussion below explores the potential erosion of the effectiveness of the overall kinetic-energy interceptor configuration by expected penetration aids.

B. Penetration Aids and Discrimination

Booster decoys are difficult. Thus, decoys do not impact the boost phase directly other than by lengthening it by the time required to deploy them. They do, however, degrade overall effectiveness by degrading the effectiveness of downstream defenses. If downstream degradation becomes great enough, the boost phase can be forced to attempt increasingly difficult intercepts, which have decreasing marginal utility.[5] Thus, the ability to discriminate trades off directly against SBI numbers and performance.

For 10% boost-phase leakage, the launch of 1,000 heavy missiles with 10 RVs per missile and 100 decoys per RV, which is less than the decoy load possible, would produce a threat of ≈ 100,000 objects. In the absence of discrimination, intercepting all of them with C_I ≈ \$2M GBIs would cost ≈ \$200B, or ≈ \$200B/\$5B ≈ 20 times the cost of the SBIs and about as much as all of the missiles. For fewer or less effective SBIs, the cost of nondiscriminating GBIs could approach ≈ \$2T.

With very large numbers of objects only a fraction could be intercepted; some targets would be destroyed. For military targets, the most efficient defense would then be a preferential defense. The number of objects in midcourse is $(1+D)mqM$, where D is the number of decoys per RV, m the number of RVs per missile, and $q = 1-p$ the probability of boost phase leakage. If the objects attacked N targets uniformly, that would give $(1+D)mqM/N$ objects per target.

By committing a like number of interceptors, any given target could be saved. A total of I interceptors could protect $I/((1+D)mqM/N)$ targets, or a fraction $I/(1+D)mqM$ of the total N. Adaptive preferential defenses, which defend most strongly those

targets that are lightly attacked because of fluctuations in the boost-phase defense, could do slightly better.[6] If it is required that a given number N_S of the targets survive, the number of interceptors required is then

$$I = (1+D)mqM\sigma, \tag{3}$$

where $\sigma \equiv N_S/N$. The total cost for interceptors is then

$$C \approx [C_K/f + C_I(1+D)mq\sigma]M, \tag{4}$$

which is shown in Fig. 1. The abscissa is the number of credible decoys per RV; the ordinate is the total interceptor cost. D ranges from 0 to 100, although a heavy missile like the SS-18 could carry many more decoys per RV.[7]

The costs start at \$7B at D = 0, as estimated above, then rise with slope $C_I mq\sigma M$ to ≈ \$105B at D = 100 for s = 0.5, i.e., half of the targets protected. Even for s = 0.1, a minimal 100 missile retaliation, it would rise to ≈ \$25B, which represents a 350% cost increase over the undecoyed threat. Such increases would make the boost layer a 20% part of the total cost, and hence dilute the advantages of inexpensive or brilliant interceptors. This figure is for a 90% effective boost layer. The cost of a purely midcourse layer can be seen by setting p = 0, which would cause all costs to rise 10-fold to ≈ \$1-2T.

This calculation assumes that both the boost and midcourse layers are always in the mix and that their proportions are related by the required attrition. For some parameters either the boost or midcourse layer alone could be preferable to both. The transitions between them have been studied elsewhere; they do not alter the results or conclusions derived here significantly.[8]

The number of objects in midcourse could be reduced through reducing boost-phase leakage by increasing the number of SBIs. However, SBIs have a finite flyout velocity, and the added SBIs would have less time to respond to missed missiles, so the added SBIs would have to be as densely distributed as the first layer to intercept missiles that leaked through it. If so, the second SBI layer could be about as large as the first, in which case it could cost ≈ \$100B to intercept another ≈ p(1-p)M ≈ 90 missiles, which would give a cost per intercept ≈ \$100B/90 ≈ \$1B/missile,

or \$100M/RV. That is roughly the same as nondiscriminating GBIs. Thus, to retain any margin of effectiveness against decoyed threats, good discrimination is required.

C. Discrimination

Providing discrimination for the GBIs can be more effective. If 90% of the 100 decoys were discriminated, the remaining 10 decoys and their RV could be intercepted for ≈ 11 x \$2M/GBI = \$22M, which is comparable to the ≈ \$200M/missile ÷ 10 RV/missile ≈ \$20M/RV cost of RVs from heavy missiles.[9] The interceptor costs of such a midcourse layer would require ≈ 1,000 leaking RVs x (1+10 decoy)/RV ≈ 11,000 GBI, which would cost ≈ \$22B.

Better discrimination would reduce the number of GBIs needed. For 99% discrimination, the midcourse costs would be down to about the original \$2B, plus the cost of discrimination. With this level of discrimination, GBIs could be effective without SBIs. Their cost per kill would remain at ≈ \$20M per missile independent of the compression of the boost-phase threat in space and time, while the cost of GBIs would rise to about \$100M/missile after threat modernization, i.e., the introduction of fast-burn missiles in compact launches.[10] If discrimination could eliminate a fraction ϵ of the attacking objects, there would still remain $D(1-\epsilon)$ credible decoys per RV and a total of

$$\beta \equiv [1+D(1-\epsilon)]m \qquad (5)$$

credible objects per missile. For this β, Eq. (3) becomes

$$I = \beta q M \sigma$$

and the total cost for interceptors becomes

$$C \approx (C_K/f+C_I\beta q\sigma)M, \qquad (6)$$

which is shown in Fig. 2. The abscissa is the fraction of the decoys discriminated ϵ; the ordinate is total interceptor costs. The top curve is for 50 decoys per RV; the middle is for 30; and the bottom is for 10. For low discrimination, the increase in costs is essentially proportional to D. For $\epsilon \approx 0.5$, the increases are factors of two. The penalties are larger when the attacker optimizes the number of decoys.

D. Discrimination Availability and Cost

In the absence of defenses, no decoys are needed. Hence, few are deployed today. If defenses were deployed, decoys would be, too. The experience of this decade's research indicates that developing decoys that could negate developed passive and active sensors could take 3-5 years, which means that they could be in place at the time of the first operational capability of SBIs. Their cost should be modest; offloading 1-2 reentry vehicles per heavy missile should provide several tens of decoys for each of those remaining. In the absence of good defenses, that could be enough to degrade the defense unacceptably.

The price for midcourse margin is essentially that of discrimination.[11] Briefly, passive infrared and active radars are developed, but are compromised by their inability to see inside objects or measure their masses. Large infrared satellite sensors lack the sensitivity and resolution to provide RV trajectories, although ground-based infrared probes could act as bulk filters and establish tracks. Current passive discrimination could only eliminate about every other decoy, which is negligible.

Neutral particle beams (NPBs) can penetrate objects and directly measure their masses, the one parameter of a weapon that decoys cannot afford to duplicate. Thus, they are the only sensors that can discriminate with certainty between RVs and decoys.[12] For predeployment in space, about 20 NPBs would be required to discriminate the unattenuated threat.[13] For popup deployments, 2-4 NPBs could suffice.

The NPB platforms could cost about \$200-500M apiece. If in the near term, each popup could discriminate 100-1,000 objects/s, in the $\approx$ 1,000 s of midcourse available to popups, each could discriminate 10^5-10^6 objects, so that one popup could address a 10-fold attenuated threat and about 10 could discriminate the full threat. If so, near-term discrimination could cost \$0.5-5B.

The development of popup platforms should be less stressing than that of platforms that are to remain on orbit for a decade,

so the popups could be available roughly as soon as the SBIs.[14] Popups are also useful because of their lack of absenteeism and high level of intrinsic survivability.[15] They are also modular. As additional decoys or missiles were deployed, more NPBs could be added to offset them. There is no threshold constellation size for coverage and effectiveness.

The actual availability of discrimination depends on research, development, and funding. NPB discrimination could with resolve be available in as little as five years; current programs could delay it several decades. Cost and effectiveness of discrimination are less uncertain than its availability and rate of introduction. For the purposes of this study, it is sufficient to parameterize discrimination as growing in time as

$$\epsilon = 1-e^{-kt}, \qquad (7)$$

where k is a discrimination growth rate that reflects the number and performance of platforms deployed, which is varied over likely values as described below.

III. THREAT VARIATIONS

As noted above, the threat adjusts the number of decoys to the level of discrimination expected. Poor discrimination only justifies a small diversion of payload into penaids; good discrimination could divert almost all. The attacker could determine the quality of the defense's ability to discriminate ϵ, by observing its testing. Its quantity could be determined from the deployment and dispositions of its sensors. The basic criteria are the minimization of the payload diverted to deliver a given number of penetrating RVs or the maximization of damage for given costs. They are dual problems at this level. Their solution is addressed in stages below.

A. Maximize Threat Objects

Decoys can dilute the effectiveness of midcourse defenses with imperfect discrimination. It is useful to find the combination of payload and decoys that maximizes the number of credible decoys that could be deployed. Deploying a decoy

requires the removal of about twice its mass in weapons, when both the mass of the decoy and that of the mechanism to deploy it are accounted for. If D decoys were deployed with each RV, the number of weapons remaining on each missile is

$$m \approx m_o(1-\alpha D), \tag{8}$$

where $m_o = m(D=0) \approx 10$ is the undecoyed payload of current heavy missiles, $\alpha \approx 2M_D/M_W$, and M_D and M_W are the mass of a decoy and weapon, respectively. For 1% decoys, i.e., decoys whose masses are about 1% of a weapon, $\alpha \approx 0.02$ and $m = m_o(1-D/50)$.

This nominal $\alpha = 0.02$ should be attainable in the near to midterm. It could be reduced further, depending on the quality of discrimination possible then and in the long term. The attacker should minimize α to maximize m, but α cannot be reduced freely, because it reflects the difficulty of making and deploying credible light decoys.

Given α and m_o, the attacker maximizes the number of credible decoys in the threat, Eq. (5). For $\epsilon << 1-\alpha$, modest discrimination, and light decoys, β is maximized by the choice

$$D_o = [1-\alpha/(1-\epsilon)]/2\alpha, \tag{9}$$

which is shown in Fig. 3 as a function of ϵ. When ϵ approaches $1-\alpha$, the optimal number of decoys falls rapidly. D_o varies inversely with α and ϵ. For $\alpha << \epsilon << 1$, $D_o \approx 1/2\alpha$; for $\alpha = 1/50$, D_o approaches 25, as observed in Fig. 3. The optimal number of decoys from Eq. (9) can be substituted into Eq. (5) to determine the number of credible objects per missile

$$\beta_o = \beta(D_o) = m_o(1+\alpha-\epsilon)^2/4\alpha(1-\epsilon), \tag{10}$$

which is shown in Fig. 4. For $\alpha << \epsilon << 1$, Eq. (10) reduces to

$$\beta_o \approx m_o(1-\epsilon)/4\alpha, \tag{11}$$

which produces the constant slope $d\beta_o/d\epsilon \approx -m_o/4\alpha$. Overall the number of decoys per RV remains large up to high levels of discrimination, but the number of RVs drops almost linearly to compensate for the impact of increasing discrimination.

B. Maximize Penetrating RVs

The above optima are relevant, but are derived under the assumption that the attacker simply wants to maximize the number

of objects in the threat. In reality the attacker wants to maximize the number of penetrating RVs. The optima for that metric are related to those above. If the defense has I interceptors, it can fire approximately I/mM at the cloud of objects concealing each of the mM RVs.

The probability of an interceptor fired randomly at an object in one of the clouds and hitting an RV in it is approximately m/β; the probability of missing is $1-m/\beta$. The probability that an RV survives is the probability that all of the interceptors fired at it miss, which is $(1-m/\beta)^{I/mM}$. Thus, the expected number of penetrating RVs is approximately

$$R = (1-m/\beta)^{I/mM} \cdot mM, \tag{12}$$

which is shown in Fig. 5 for I = 20K, i.e., twice as many interceptors as RVs, and α = 1%. The bottom curve is for ϵ = 0.95, which is good discrimination; those above it are for ϵ = 0.85, 0.7, and 0.5, respectively. For the top, the maximum is at about 15 decoys. The number of penetrating RVs is about 6.5K. For poor discrimination, even twice as many interceptors per RV reduces the threat by about 30%. For ϵ = 0.7, the peak shifts to about 20 decoys per RV, but the penetration remains at about 55%.

For 85% discrimination, the peak shifts to about 25 decoys and the peak falls to about 4K. That number would still, however, be enough to put an average of 2 RVs on each of 2K military targets, which would not be acceptable. For ϵ = 0.95, the peak shifts out to about 30 decoys, which produces about 1.5K penetrating RVs. That would drop below 1 RV on each of 2K military targets, but would still be marginal. That essentially represents the threshold of military utility; the levels of discrimination required for the defense of value would be much higher, because it is concentrated in ≈ 300 metropolitan areas.

Figure 6 shows the corresponding βs. For low levels of discrimination, they peak at ≈ 130; for ϵ = 0.7, they fall to ≈ 80; for 0.85 to ≈ 40; and for 0.95 to ≈ 20. All of the maxima occur at about 40-50 decoys. The peak value decreases and shifts to a lower D as α increases. Thus, the magnitude of the credible

objects per missile corresponds roughly to those from Fig. 4 for corresponding conditions.

The main difference is that in this penetration maximizing calculation, no decoys are used against weak discrimination. It is interesting that the number of decoys for maximum objects decreases with ϵ while that for the number of penetrating decoys increases. It is useful that the number of decoys used increases faster than linearly with large ϵ. Equation (12) can be inverted to give the number of interceptors needed to enforce a given level of penetration

$$I = mM \cdot \ln(R/mM)/\ln(1-m/\beta), \tag{13}$$

which is shown in Fig. 7 for m and β as defined before. D is reoptimized slightly at each ϵ. The upper curve is for R = 1K penetrations; the bottom is for 2K. For low ϵ, the top is at about 170K; the bottom is at 110K. Both are large and in accord with the magnitudes of the unoptimized calculations of Fig. 2. To achieve either would take $\approx$ 5K-10K interceptors even for ϵ = 0.98, again showing that very good discrimination is required for value.

These optima can be explored as before but are less analytically tractable. If Eq. (13) is differentiated, ignoring the variation of the logarithmic factor, the result is that the maximum of I_o occurs at the same D_o, in Eq. (9), that maximizes the number of objects. The logarithm does, however, shift the optima shown in Fig. 5.

The fundamental objective of the attacker would be, as stated above, to minimize the cost of producing a given amount of penetration. For that optimization payload, mass could be used as a surrogate for dollar costs, since the technology levels and hence the cost per unit mass of the attacking and defensive payloads should be comparable. The formalism above is relevant. All that is needed is to assign a cost or mass to discrimination, and then Eq. (13) could be differentiated with respect to I and ϵ at constant R to find the combination that minimizes cost.

Because that procedure is related to that leading to Eq. (13) and the results are related to their optima, this program is

not carried further here. For the parameters above and any reasonable discrimination costs, the optimum lies at the maximum level of discrimination that is technically feasible. The formalism used below assumes that can only be approached as technology and deployments evolve.

IV. COST OF DEFENSE

This section discusses the costs of discrimination, both its actual costs and the shadow costs associated with the additional interceptors needed if discrimination is inadequate. It starts with the formalism for discounting costs.

A. Discounted Costs

The incremental costs for boost and midcourse defenses and discrimination in any year is

$$C' = C_K \cdot K' + C_I \cdot I' + C_D \epsilon', \qquad (14)$$

where C_K is the cost of a boost-phase defender, C_I that of a midcourse interceptor, and K' and I' are the total defender and interceptor deployments in that year. $C_D \approx \$0.5\text{-}5B$ is the cost of full discrimination, and ϵ' is the increment toward it in that year, which is evaluated from Eq. (7). This bulk treatment of discrimination is justified by the uncertainty in its costs and the fact that it is likely to be small relative to interceptor costs whenever it is essential.

The relevant quantity for comparing costs is the current costs of the various defenses discounted at the appropriate discount or interest rate i (%/yr) back to the beginning of deployment

$$C = \Sigma_0{}^{\theta} dt\ e^{-it} C'(t) = \Sigma_0{}^{\theta} dt\ e^{-it}(C_K K' + C_I I' + C_D \epsilon'), \qquad (15)$$

where θ is the end of the initial phase in which decoy deployment and discrimination are dominant and after which boost-phase modernization must also be treated.[16] This discounted cost must be less than the discounted costs of the threat for the defenses to be effective.

B. Component Costs

The variation of K, I, and ϵ with time have been discussed above. It is only necessary to convert them into the proper annual increments to derive the discounted costs that form the basis for the selection between alternative deployments.

1. Boost Phase

In the absence of boost-phase threat modernization, the number of defenders that must be deployed initially is $K \approx M/f$. It is of course necessary to deploy additional defenders to make up for failure on orbit, which occurs roughly at a rate g(%/yr), so the total annual defender increment is

$$K' = \delta(t)K + gK = [\delta(t) + g]K, \tag{16}$$

whose contribution to the total discounted cost is

$$\begin{aligned} \delta C_K &= \Sigma_0{}^{\theta}dt\ e^{-it}C_K K' = \Sigma_0{}^{\theta}dt\ e^{-it}[\delta(t)+g]C_K M/f, \\ &= [1+g(1-e^{-i\theta})/i]C_K M/f, \end{aligned} \tag{17}$$

which for $\theta >> 1/i$ reduces to $\approx C_K M/f(1+g/i)$. The discount rate i essentially defines the time horizon of interest. For evaluating R&D projects, $i \approx 5\%/yr$ is typically used, which would give a horizon of $1/i \approx 1/5\%/yr \approx 20$ years.

For a transition time of 20 years, that would give an exponential of $e^{-1} \approx 0.37$, so that most costs would have been accounted. θ being much larger would only increase the second term about a third, which would only increase dC_K by $\approx 15\%$. Conversely, $\theta = 10$ years would give $e^{-i\theta} \approx 0.6$, which would decrease dC_K by $\approx 15\%$. Because $i = 5\%/yr$ is standard and $\theta \approx 20$ years is a common assumption, the calculations below are not sensitive to the details of the discounting, which is in any case that used in calculating the present value of any bond or mortgage.

2. Midcourse Interceptors

For ϵ of the form of Eq. (7), the approximate form of the optimum number of objects from Eq. (11) becomes

$$\beta_o \approx m_o(1-\epsilon)/4\alpha \approx m_o e^{-kt}/4\alpha, \tag{18}$$

for which the number of decoys deployed falls at the same rate at which the quality of discrimination increases. It is useful to use the growth of discrimination of Eq. (7) to see how the number of objects per missile grows. Figure 8 shows ϵ and β_o as functions of time for several values of the growth rate k. The parameter ϵ starts at 0 and then grows rapidly. The top curve is for k = 30%/yr; the second is for 20%/yr; and the bottom for 10%/yr. The figure is for 1% decoys, or $\alpha = 0.02$, so β_o starts at 125 for short times and then falls. For t = 0, it follows from Eq. (9) that the optimal $D_o \approx 1/2\alpha$, which for $\alpha \approx 0.02$ is $\approx$ 24 decoys per RV.

That is close to the economic break point for midcourse interceptors. For heavy missiles costing ≈ \$200M apiece, their RVs cost ≈ \$200M/missile ÷ 10 RV/missile ≈ \$20M/RV. Thus, a cluster of objects with one RV and 10 decoys would have an average value per object of ≈ \$20M/RV ÷ 11 objects/RV ≈ \$2M/object. That is about the price of a GBI, thus at or below about 10 decoys per RV, it becomes acceptable to kill them all. Unfortunately, for $\alpha = 2\%$, there are $D_o \approx 1/2\alpha \approx 24$ decoys/RV, and at $\alpha = 1\%$ decoys, there are ≈ 50/RV. As the number of RVs drops, the value of the missile resides in fewer and fewer RVs, which helps the effectiveness of the defense, but current buses for heavy missiles have enough fuel for cross targeting to provide another 100 decoys per RV without offloading. Thus, it is necessary to be able to take large numbers of decoys and reduce their number to below the 5-10/RV that can be addressed directly.

Using 5 objects/RV as the GBI break point, and Eq. (18) for β_o shows that if initially $\beta_o/m > 5$, then for growth rate k, it will take about $t_5 \approx k^{-1}\ln(m_o/20\alpha)$ to decay to an economic level. For $\alpha = 0.02$ and k = 0.1%/yr, this gives $t_5 \approx 10\cdot\ln(2.5) \approx 8$ years, as seen in Fig. 8. This means that for the first decade after deployment, the GBIs would not meet the cost effectiveness criteria and should be excluded.[17] Since the boost-phase interceptors also face diminishing marginal returns, that portion of the threat leaking through the boost phase simply would not be

met during that decade. The penalty for doing this is the shadow price of not having adequate discrimination.

With the functional form for β_o of Eq. (18), the number of midcourse interceptors becomes

$$I = Mq\sigma\beta = Mq\sigma m_0 e^{-kt}/4\alpha \equiv I_0 e^{-kt}, \tag{19}$$

so that I starts large and then decays if the rate of growth of discrimination is appreciable. The initial expenditure for midcourse interceptors is $C_I I_0$, which gives a contribution to I' of $C_I I_0 \delta(t)$. If they also failed at rate g, the total annual increment for interceptors would be

$$I' = \delta(t) I_0 + gI = [\delta(t) + ge^{-kt}] I_0, \tag{20}$$

whose contribution to the total discounted cost would be

$$\begin{aligned} \delta C_I &= \Sigma_0{}^{\Theta} dt\ e^{-it} C_I I' = \Sigma_0{}^{\Theta} dt\ e^{-it} [\delta(t) + ge^{-kt}] C_I I_0, \\ &= [1+g(1-e^{-(i+k)\Theta})/(i+k)] C_I I_0, \end{aligned} \tag{21}$$

which for $\Theta >> 1/i$ reduces to $\approx C_I I_0 [1+g/(i+k)]$. Thus, the effective discount rate is increased by discrimination, which means that the effective costs of interceptors are decreased.

3. Discrimination

Discrimination is taken to be initially $\epsilon = 0$, the likely outcome of current programs. Its subsequent rise is given by Eq. (7), from which

$$\epsilon' = d\epsilon/dt + g\epsilon = g + (k-g)e^{-kt}, \tag{22}$$

so that

$$\begin{aligned} \delta C_D &= \Sigma_0{}^{\Theta} dt\ e^{-it} C_D \epsilon' = \Sigma_0{}^{\Theta} dt\ e^{-it} [g+(k-g)e^{-kt}] C_D, \\ &= [g(1-e^{-i\Theta})/i + (k-g)(1-e^{-(i+k)\Theta})/(i+k)] C_D. \end{aligned} \tag{23}$$

When Θ is large, this reduces to $\approx C_D[g/i+(k-g)/(i+k)]$, which reduces to ≈ 1 for $k >> i >> g$, which shows that for high-deployment rates, it is only necessary to pay for discrimination once. Decoys and interceptors then revert to predecoy levels.

C. Cost of First Phase

The current value of the two phase 1 defense cost streams is calculated by summing those Eqs. (17), (21), and (23) to obtain

$$\begin{aligned} C = {} & [1+g(1-e^{-i\Theta})/i] C_K M/f + [1+g(1-e^{-(i+k)\Theta})/(i+k)] C_I I_0 \\ & + [g(1-e^{-i\Theta})/i + (k-g)(1-e^{-(i+k)\Theta})/(i+k)] C_D. \end{aligned} \tag{24}$$

An expression that is correct for long times and also useful for shorter ones may be obtained by summing the expressions below to obtain

$$C \approx (1+g/i)C_K M/f + [1+g/(i+k)]C_I I_0 + [k(i+g)/i(i+k)]C_D . \quad (25)$$

For a nominal i = 5-10%, the criteria for its use are roughly that $\theta > 1/i \approx$ 10-20 years, which is roughly the time that could well transpire before large modernization of boost-phase offenses and defenses were addressed.

As derived, this cost strictly represents only the investment costs for the interceptors; their operating costs must also be accounted for. It is generally the case, however, that the lifetime operating costs of such systems are roughly equal to their initial investment costs. To the extent that is true, operating costs can be taken into account by roughly doubling the unit investment costs C_I and C_K. That correction is included in the costs used above, which are current estimates of the lifetime operating costs of those components. While accurate from an accounting viewpoint, this approximation shifts all operating costs forward to the point of purchase, which increases discounted costs. The corrections needed should, however, be smaller than the uncertainties in the defenders' costs.

D. Results

The costs from Eq. (24) are shown in Fig. 9 for the nominal near-term parameters discussed above, with replacement at g = 7%/yr, and with a transition at θ = 20 years. The abscissa is the discrimination growth rate; the ordinate is the total discounted interceptor costs. The three curves correspond to the $0.5, $2.5, and $5B costs for full discrimination discussed earlier. The curves are roughly parallel. Each falls 30-40% as k increases from 0, with no discrimination, to k = 25%/yr, which is a rapid buildup in terms of the curves of Fig. 8. The curves are separated by a few billion dollars. The curves are relatively insensitive to the discrimination costs below the $0.5B cost of the bottom curve. The curves greatest sensitivity are to α. The curves all scale essentially as $1/\alpha$ when k is

small, which is plausible from Eq. (24), since interceptor costs are then dominant and I_0 is proportional to $1/\alpha$. While higher discrimination growth rates do decrease total costs significantly, the reduction is apparently much smaller than that seen in Fig. 2. The reason for that is explored below.

V. AVAILABILITY OF DISCRIMINATION

The rough calculations of Figs. 1 and 2 show an order of magnitude cost reduction for good discrimination; Fig. 9 only shows ≈ 50%. The difference is in their assumptions about the availability of discrimination at the outset of the deployment of defenses. Deploying defenses induces the attacker to deploy many decoys per RV. If discrimination is present from the outset, it reduces the optimal number of decoys deployed and hence the number of interceptors purchased. If discrimination is not available at the outset, enough interceptors must be purchased to meet both the RVs and their decoys. This initial purchase is typically so large that what happens later cannot offset its impact on discounted costs.

An alternative approach to the midcourse is to not buy the interceptors and simply not meet the threat. That is essentially what programs would do that advocate purchasing few interceptors and no discrimination. The analytical approach of Fig. 9 is correct for current policies, which delay discrimination relative to interceptors, but those policies lead to defenses with little or no margin of effectiveness relative to the cost of the threat.

It is straightforward to analyze the economics of defenses that have significant discrimination from the outset. The equations for the boost-phase component costs are unchanged. The modifications of the equations for midcourse interceptors and discrimination are minor and straightforward; they are addressed below.

A. Analysis

If the level of discrimination starts not from zero but from some level $\epsilon(t=0) = \epsilon_o$ and grows thereafter at rate k, at a later time t, it has the value

$$\epsilon(t) = 1 - (1-\epsilon_o)e^{-kt}. \tag{26}$$

Thus, at that time the optimized number of objects per missile is

$$\beta_o \approx m_o(1-\epsilon)/4\alpha \approx m_o[(1-\epsilon_o)e^{-kt}/4\alpha+1/2], \tag{27}$$

where the last term is added to account for the $\approx m_o/2$ interceptors needed to intercept the $m_o/2$ RVs from each penetrating missile even for perfect discrimination. Thus, the number of interceptors needed is

$$\begin{aligned} I &= Mq\sigma\beta = Mq\sigma m_o[(1-\epsilon_o)e^{-kt}/4\alpha+1/2] \\ &\equiv I_o[(1-\epsilon_o)e^{-kt}/4\alpha+1/2]. \end{aligned} \tag{28}$$

For this inventory, the annual interceptor increment is

$$I' = \delta(t)[(1-\epsilon_o)/4\alpha+1/2]I_o + g[(1-\epsilon_o)e^{-kt}/4\alpha+1/2]I_o, \tag{29}$$

whose discounted value is

$$\begin{aligned} \delta C_I = \{&[(1-\epsilon_o)/4\alpha+1/2] \\ &+g(1-\epsilon_o)[1-e^{-(i+k)\theta})/(i+k)]/4\alpha+(1-e^{-i\theta})/2i)\}C_I I_o, \end{aligned} \tag{30}$$

which reduces to Eq. (21) for $\epsilon_o = 0$. The modification for the growth of discrimination can be evaluated from Eq. (26) as

$$\epsilon' = d\epsilon/dt + g\epsilon = g + (k-g)(1-\epsilon_o)ke^{-kt}, \tag{31}$$

from which

$$\delta C_D = [g(1-e^{-i\theta})/i+(k-g)(1-\epsilon_o)(1-e^{-(i+k)\theta})/(i+k)+\epsilon_o]C_D. \tag{32}$$

The total cost is, as before, the sum of the boost, midcourse interceptor, and discrimination costs.

B. Results

The result of having varying amounts of discrimination at the outset of deployment is shown in Fig. 10. The abscissa is the initial discrimination ϵ_o; the ordinate is the total cost. The bottom curve is for $\alpha = 0.02$, i.e., 1% decoys. The middle curve is for $\alpha = 0.01$; the top is for 0.005. The curves are essentially straight, and their value at $\epsilon_o = 0$ is inversely proportional to α. If initially there is little discrimination, k is small, and θ is large, then

$$\delta C_I \approx (1/4\alpha)(1+g/i)C_I I_o, \tag{33}$$

which is inversely proportional to α and directly proportional to I_o. For $\epsilon_o \approx 0$, the slope is

$$d(\delta C_I)/d\epsilon_o = -[(1+g/i)/4\alpha]C_I I_o, \tag{34}$$

which becomes flat for large α, or heavy decoys. For the lightest decoys shown, the cost per missile to the defense would be about the same as the cost of the missile to the offense, which means that the defenses would have largely been nullified for roughly comparable costs. For good initial discrimination, the cost falls to

$$\delta C = (1+g/i)C_K M/f+(1/2i)C_I I_o+[g/i+\epsilon_o]C_D, \tag{35}$$

the terms of which are comparable in magnitude and which add to the ≈ $20B shown.

While rapid growth of discrimination is still important even with good initial discrimination, it is not as important as in the case of Fig. 9. Figure 11 shows the variation of total cost with a discrimination growth rate for initial discrimination levels of ϵ_o = 0.2, 0.5, and 0.8. The results lie between the limits analyzed above. They start about $10B above the full discrimination minimum of Fig. 10 and show a factor of 2-3 spread in cost between them.

The variation with k is less. The curve for ϵ_o = 0.2 falls slightly and then flattens out by k ≈ 10%/yr. The other curves flatten out later, but still only fall 20-30% as k varies over its likely range. Overall, the impact of a nonzero ϵ_o is much greater than that of a large k later. The reason is mentioned above. If the initial level of discrimination forces the purchase of a large number of interceptors, that expenditure is so large and is required so early that what happens later cannot impact the total discounted cost to a comparable degree. For poor initial discrimination, midcourse interceptor costs are liable to swamp boost-phase costs. Discrimination has a factor of 5-10 in reducing the impact of the many, light decoys at their optimal number.

VI. SUMMARY AND CONCLUSIONS

This article estimates midcourse threats for various boost-phase layers, derives the optimal numbers of decoys for the offense to use against specified defenses, and discusses the impact of various levels of discrimination on them. This produces an integrated picture of the trades between boost-phase attrition, midcourse defenses, and discrimination.

The analysis shows that a mixture of boost and midcourse interceptors can be very effective, but is very sensitive to the use of light decoys. The availability of the required discrimination shows some options, but little slack in development. The analysis of the optimization of the threat shows that three very different objectives--maximizing the number of objects, maximizing the number of penetrating RVs, and minimizing offensive costs--all led to a similar result for the number of decoys deployed per RV and missile. The optimal result led to simple parameterization.

A discounted cost formalism is seen to be natural for combining boost, midcourse, and discrimination costs. It shows that higher discrimination growth rates do decrease total costs significantly, but no initial discrimination growth does not reduce costs as sharply as that seen from the simple arguments given earlier. The difference is in their assumptions about the availability of discrimination at the outset of the deployment of defenses. Deploying defenses induces the attacker to deploy many decoys. If discrimination is not available at the outset, enough interceptors must be purchased to meet both the RVs and their decoys. This initial purchase is so large that later developments cannot offset its impact on discounted costs.

Not buying the interceptors would mean not meeting the threat, which would essentially be the result of programs that would purchase few interceptors and little discrimination. That leads to defenses with little or no margin of effectiveness relative to the threat. Strong initial discrimination can eliminate that problem and essentially can recover the interceptors' performance levels against undecoyed threats. With

good initial discrimination, the sensitivity to later growth is reduced.

The points are analytically interesting, but not just academic. Decoys and other penetration aids can almost certainly be used to modernize the threat faster than defenses can be deployed. Thus, to avoid inducing large numbers of decoys, which could result in comparable numbers of interceptors and levels of expenditure by the defense, it is necessary to keep discrimination in step with interceptor deployments. Ideally, the required level of discrimination should be developed and deployed before the interceptors, because that would have no adverse effect on stability. Such levels could be attained on about the time scales required, but apparently not on current programs.

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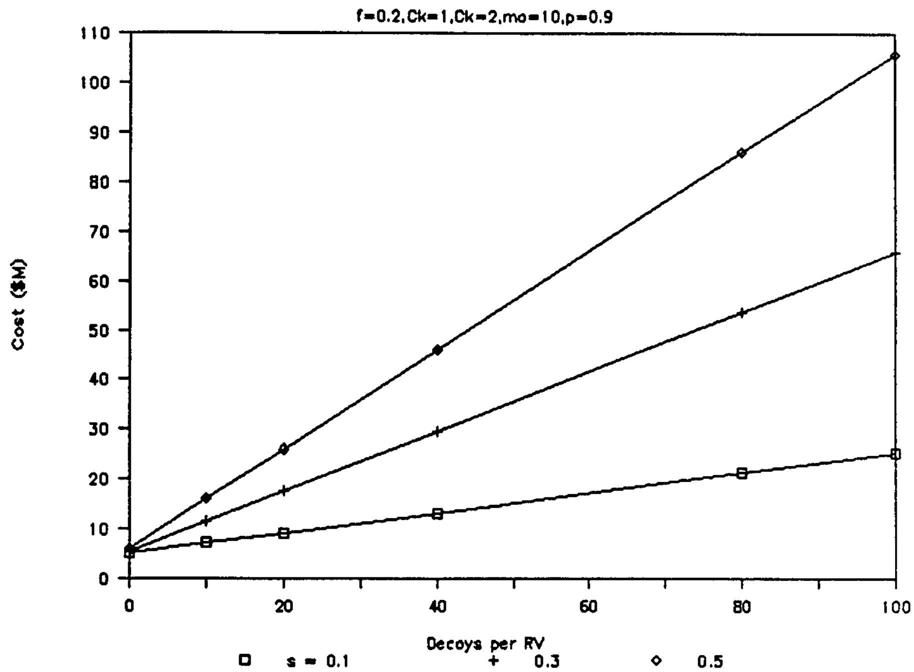

Fig. 1. Cost vs decoys

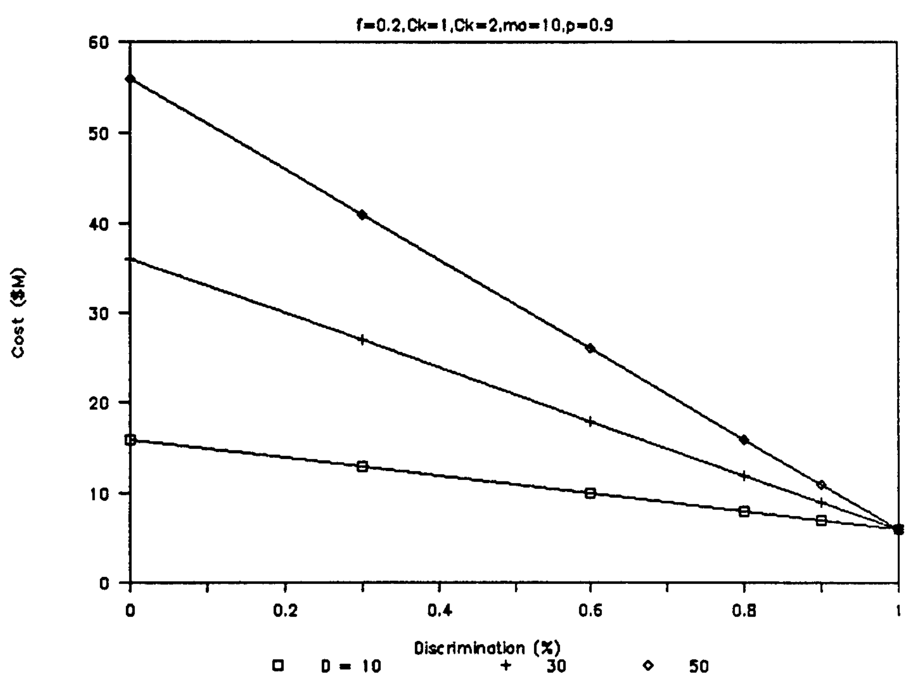

Fig. 2. Cost vs discrimination

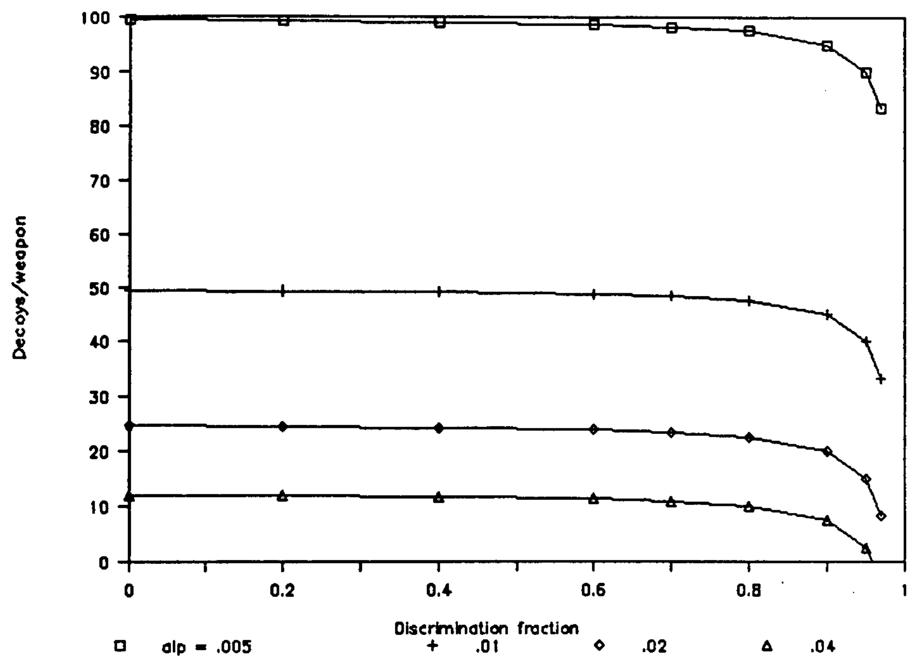

Fig. 3. Optimal decoys per weapon

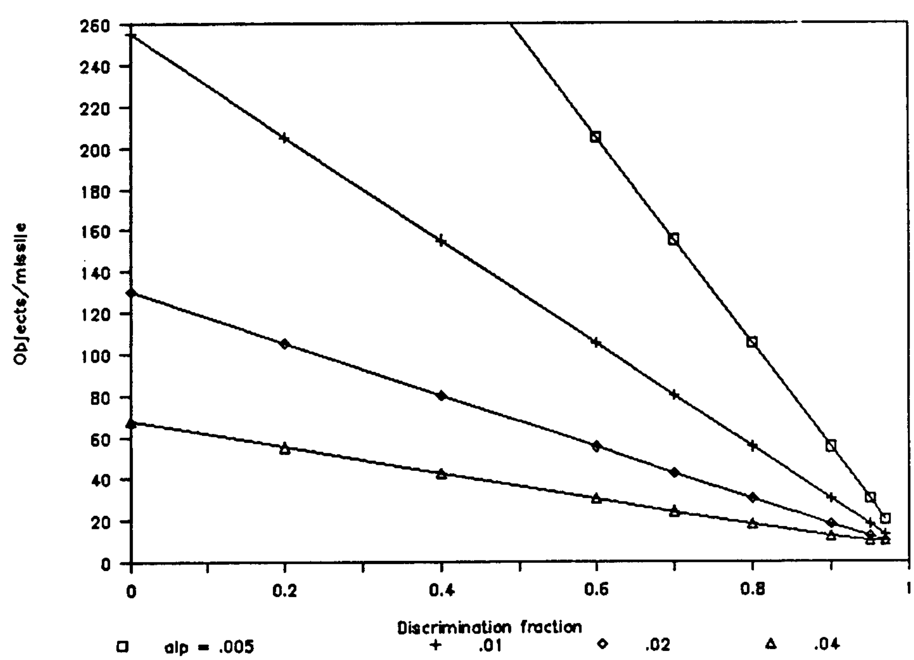

Fig. 4. Objects per missile

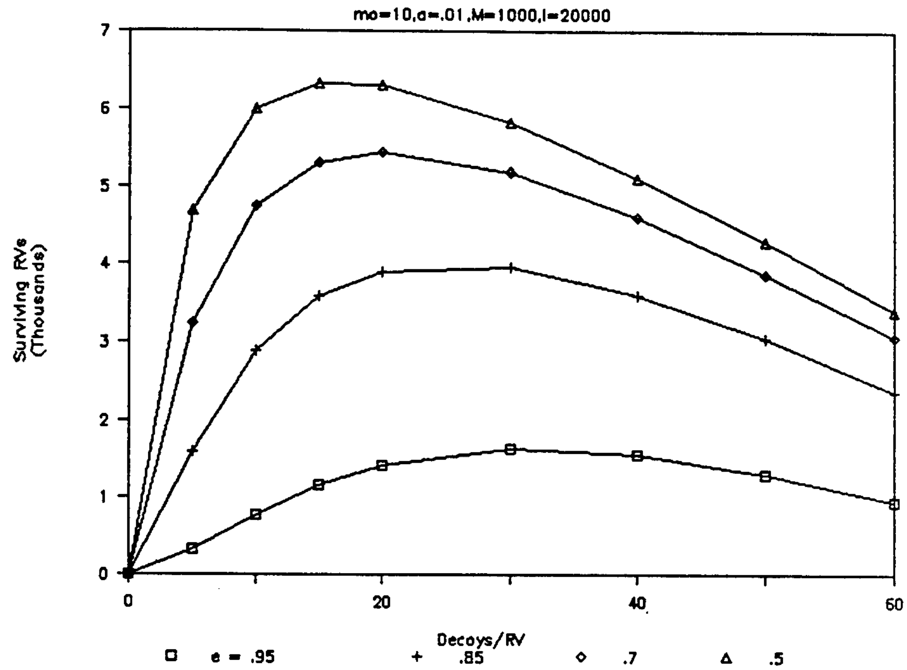

Fig. 5. Surviving RVs vs discrimination

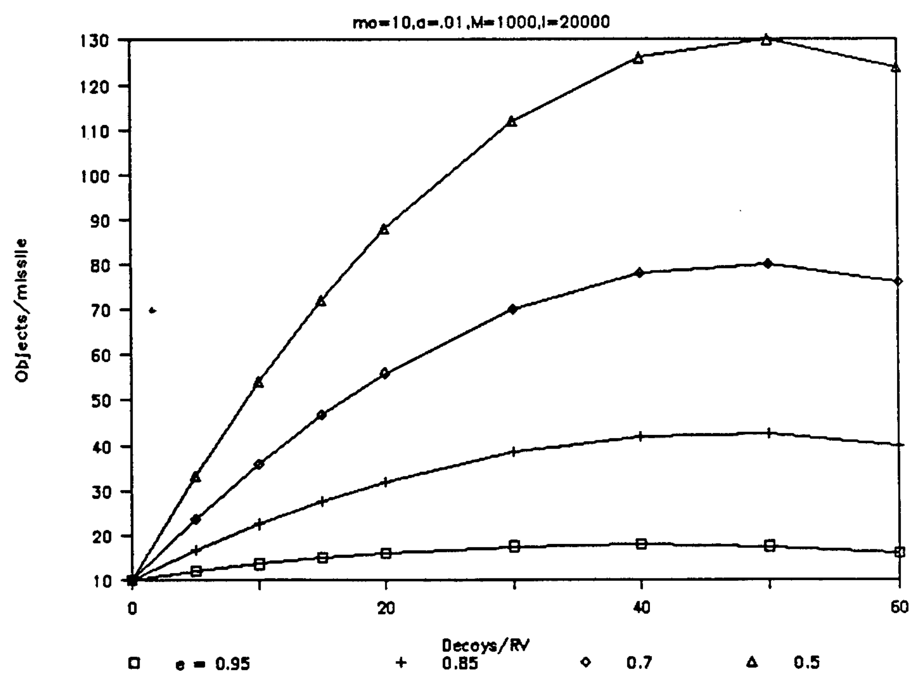

Fig. 6. Credible objects per missile

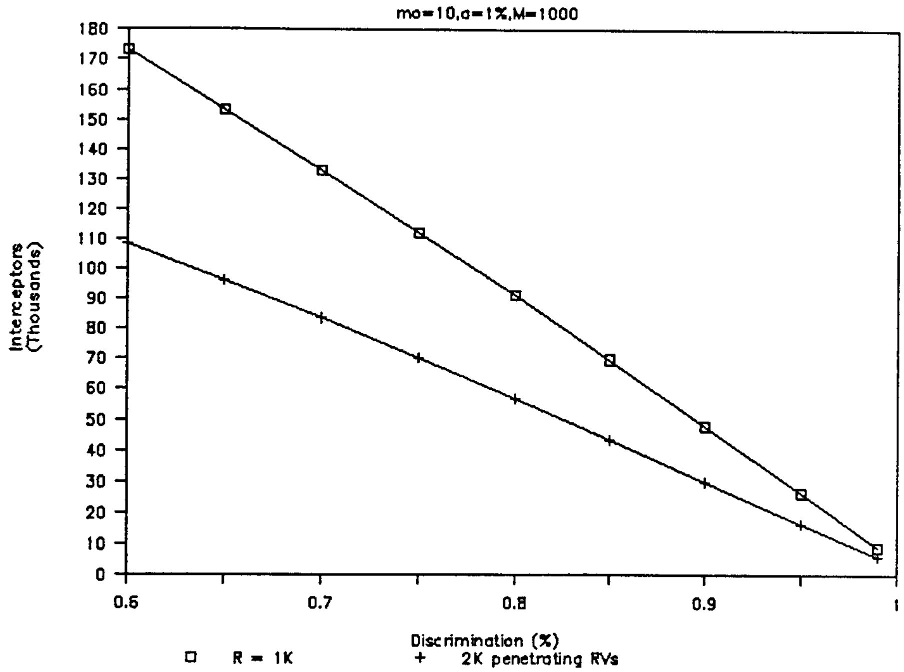

Fig. 7. Interceptors vs discrimination

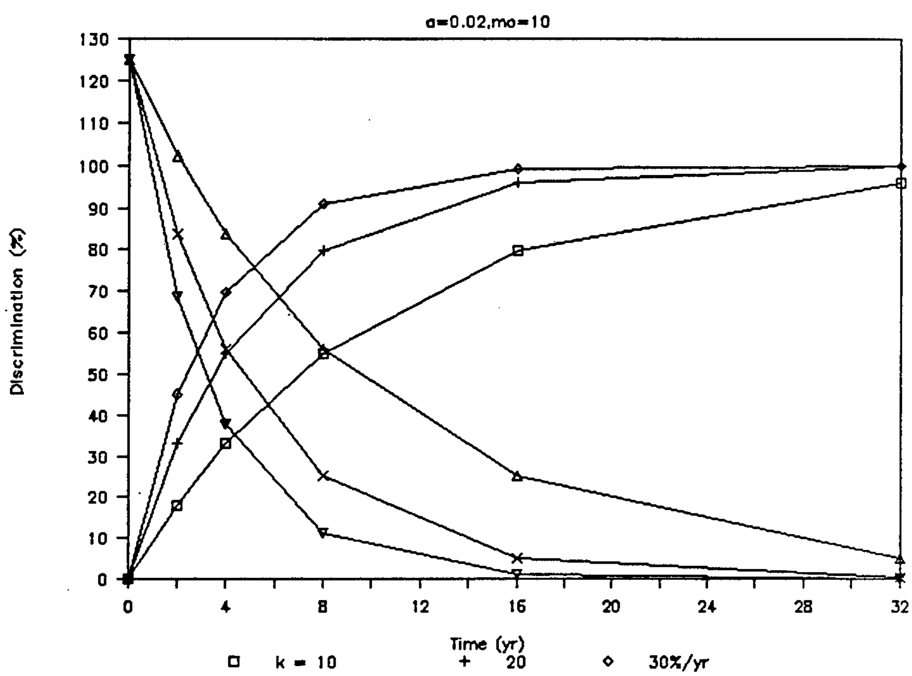

Fig. 8. Discrimination and objects

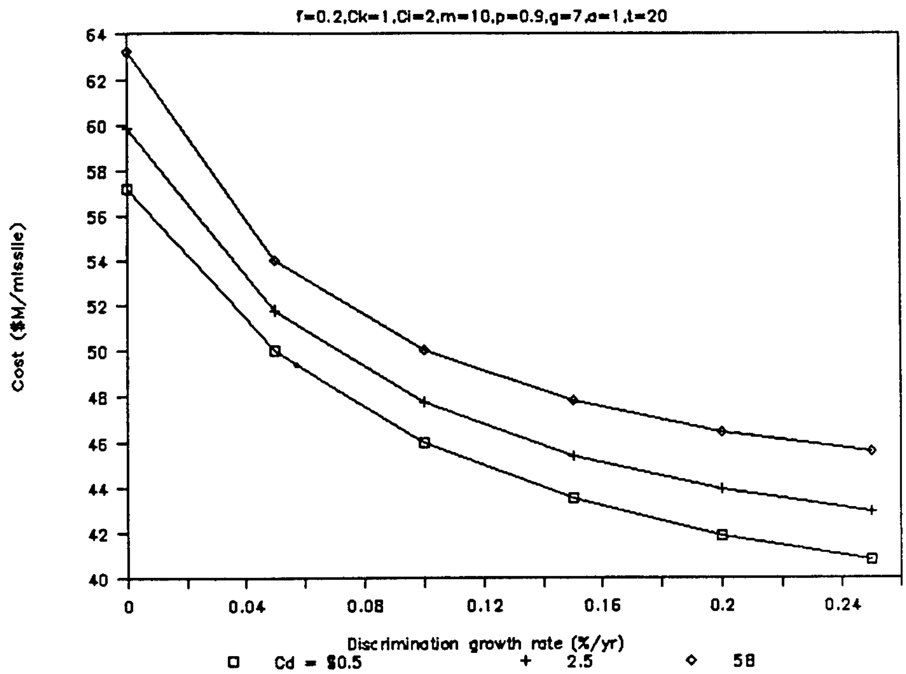

Fig. 9. Cost vs discrimination rate

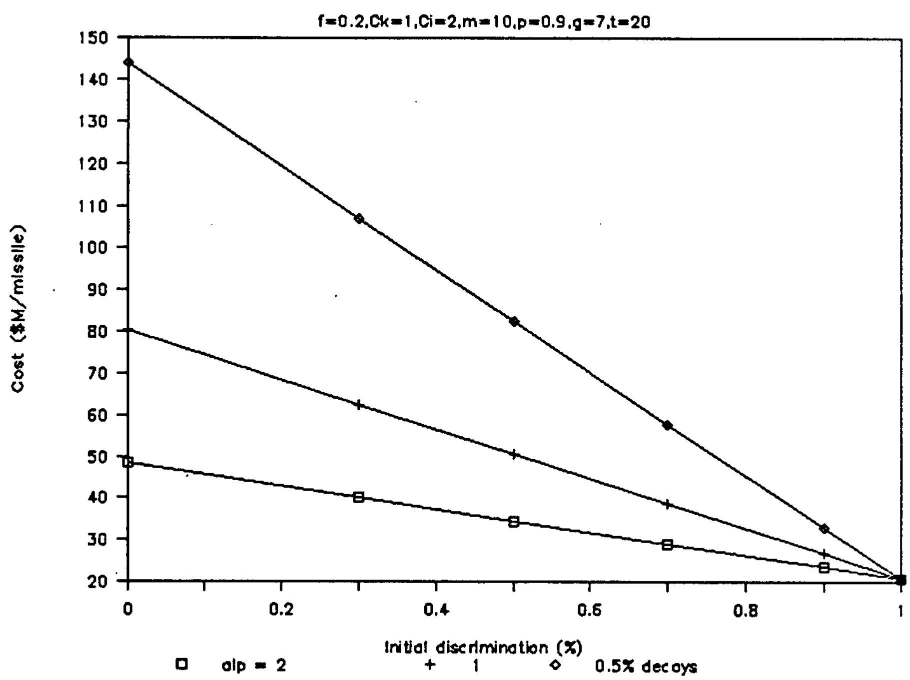

Fig. 10. Cost vs decoy mass

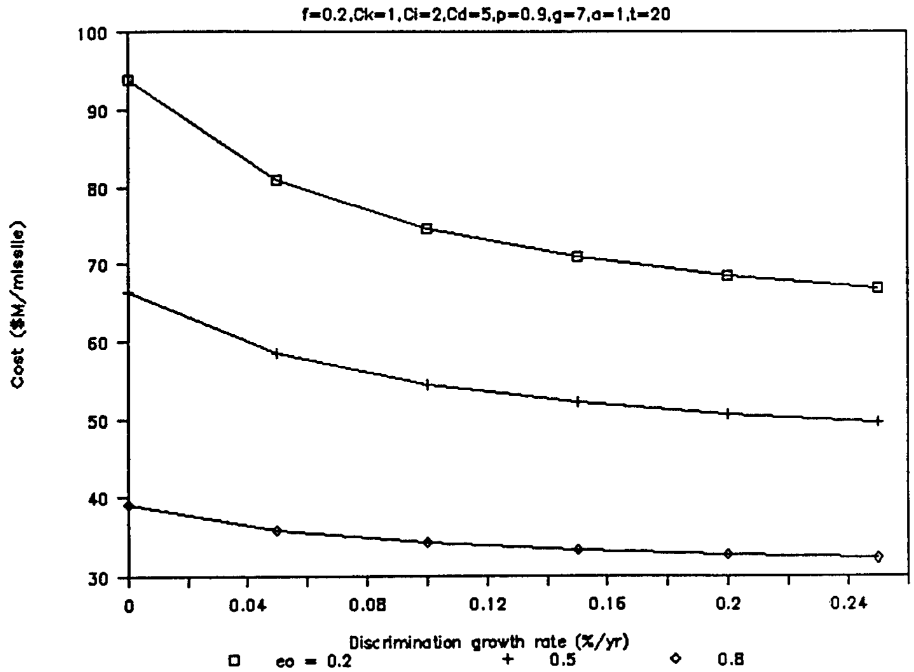

Fig. 11. Cost vs discrimination growth